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LBL Contribution to

"Reports to the DOE Nuclear Data Committee"

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Prepared for the U.S. Department of Energy
under Contract W-7405-ENG-48

LAWRENCE BERKELEY LABORATORY
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A. TABLE OF ISOTOPES PROJECT

E. Browne, J. M. H. Chong, J. M. Dairiki, D. P. Kreitz, C. M. Lederer, T. Prussin, M. E. Schwartz, M. A. Sharp, and V. S. Shirley

The publication of the seventh edition of the Table of Isotopes[1] in 1978 concluded a seven-year project involving a total effort of more than 50 man-years. Over 30,000 journal articles, reports, conference proceedings, private communications, and theses were used as source material for the present edition. In terms of both reference citations and data, the seventh edition is a factor of 4 times as large as the sixth; the complexity of the level schemes has increased even more--by almost an order of magnitude. The literature cutoff varies from about January 1977, for the lightest mass chains, to December 1977, for the heaviest.

The Table of Isotopes contains an extensive introduction which explains the scope, nomenclature, and evaluation policies used in the table. The authors' criteria for data selection are based on a determination to present the best measurements--clearly indicating conflicting results and avoiding redundancy.

The layout of the data in a single table (as opposed to the double-table format of the sixth edition) is described in Fig. 1, reproduced from the Introduction of the Table of Isotopes. Data categories included in the tabulated listings are more fully delineated in the Contents (Fig. 2). Several significant changes have been introduced in the present edition. Reported uncertainties are included for all quantities in tabular data listings. Smaller italic numbers following any value represent the uncertainty in the last place(s). A new reference-code format "journal volume page(year)" permits direct look-up of an article without the need to look up the code. A brief (12-page) list of the reference codes replaces a full bibliography, which otherwise would have increased the seventh edition by about 300 pages.

Figure 3 illustrates how a mass chain compilation is presented in the Table of Isotopes; a portion of the data for mass number A = 202 is shown. Sophisticated computer facilities and extensive programming (described in previous annual reports)[2,3] have made it possible to present the data in a variety of type sizes, styles, and intensities. The pages are thumb-tabbed by mass number for rapid data access.

This work was supported by the U.S. Department of Energy under contract No. W-7405-ENG-48.

Appendices include material of general interest to users of the Table of Isotopes (see Contents, Fig. 2). Three of the appendices deserve further comment. Appendix II contains tables of convenient standards for calibration of γ-ray, conversion-electron, and α-particle measurements. The γ-ray standard tables, prepared with the assistance

(Image size has been reduced to conform to NDC format)

II. General Features of the *Table of Isotopes*

II.A. *Layout:* An Isotope Index, ordered by atomic number (Z) and subordered by mass number (A), precedes the main table. It contains all stable nuclei, radioisotopes, and isomers that appear in the *Table of Isotopes*. (R-rated isotopes – those identified only in nuclear reactions – do not appear in the Isotope Index.) In addition to the isotope designation, the index includes the natural abundance, half-life, class (certainty of identification), and the number of the page on which the tabular data entry is found in the main table.

The main table is ordered by mass number and subordered by atomic number. For each mass number there is an abbreviated mass-chain decay scheme, showing the adopted half-lives, spin-parity assignments, and decay energies (Q-values) for the isobars, and the decay relationships between them. Noted near this scheme are the initials of the compiler(s) and, following a semicolon, those of the reviewer.

Following the mass-chain decay scheme, tabulated data and detailed nuclear level schemes are given for individual isotopes. Tabulated data entries are included for each ground state or isomer with half-life ≳1 s. A few shorter-lived isomeric species are also included – e.g., fission isomers and a few "historic" isomers, such as ^{24m}Na. The data include natural abundance, mass excess, nuclear spin, thermal neutron cross sections, all categories of data on radioactive decay, and excited-state half-lives. Data categories are shown to the left in **bold serif** type. The data are printed in sans-serif (plain) type. Each entry under a given data category concludes with the reference code or codes in braces {}. Longer data entries (radiation data in particular) begin on a new line, indented to the left of any continuation lines.

Detailed level schemes are given for each isotope (A,Z) for which there is information beyond that shown on the mass-chain decay scheme. The schemes are separated into a "decay-level" scheme, showing levels and transitions observed in the decay of all parent isotopes and isomeric states, and a "reaction" scheme, summarizing the information derived from nuclear reaction studies. Absence of a decay-level scheme, a reaction scheme, or both, means that excited levels have not been observed or that the scheme is not well established.

Decay-level schemes include all levels established in radioactive decay studies. Reaction schemes include most levels observed in nuclear reactions; when it is necessary to omit levels because of space limitations, the number of omitted levels, the energy cutoff above which they occur, and (usually) the reactions which populate them are noted in a comment. Not included are most neutron-capture resonances and other unbound states (e.g., giant resonances); these states are generally outside the scope of the present compilation, with a few exceptions in the light-element region. Some references to unbound levels other than neutron resonances are included under "other reactions" or "others".

Fig. 1. Description of data layout in the Table of Isotopes, from the Introduction. (XBL 786-9447)

(Image size has been reduced to conform to NDC format)

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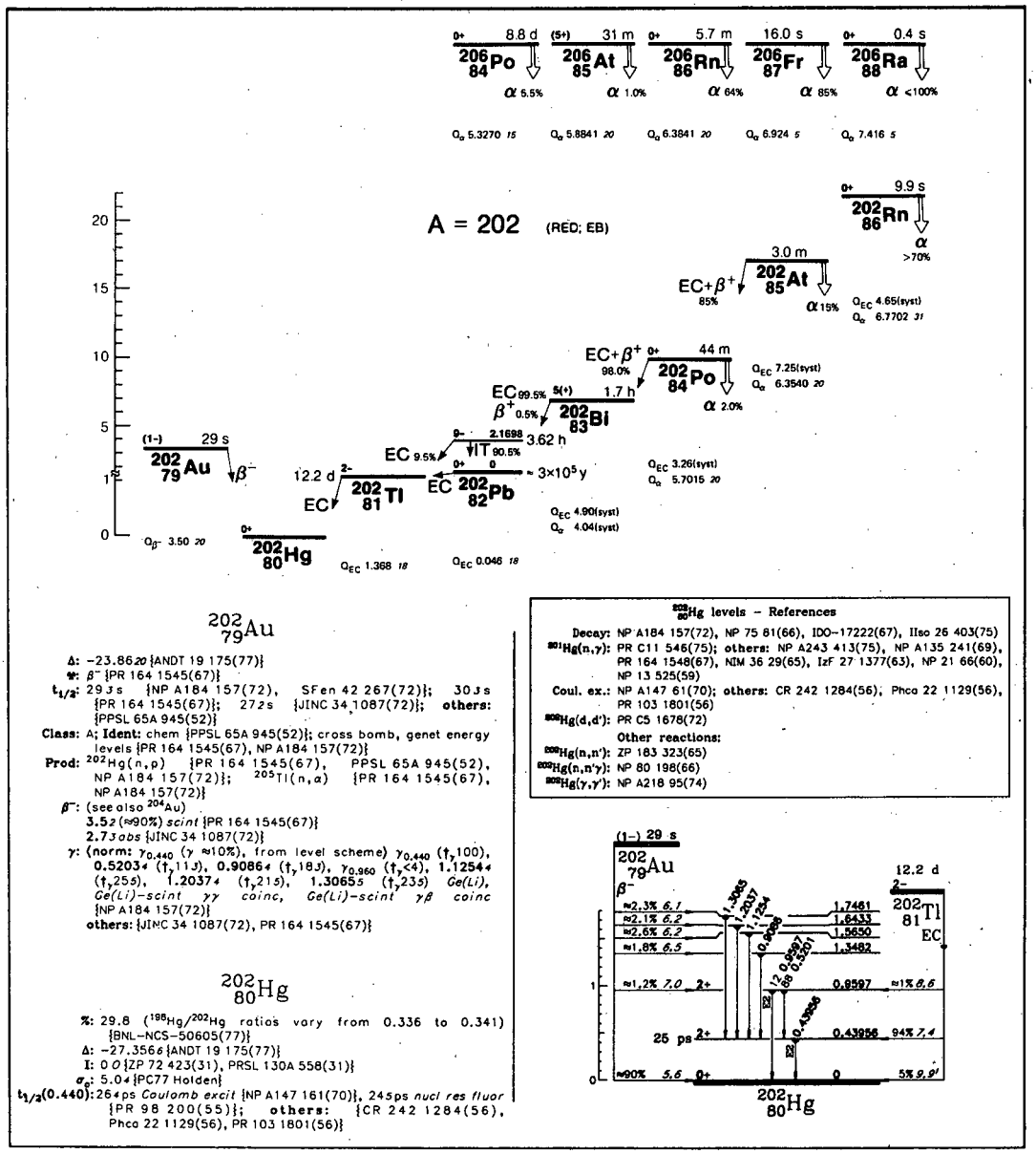
Fig. 2. Table of Contents from the seventh edition of the Table of Isotopes. (XBL 786-9448)

(Image size has been reduced to conform to NDC format)

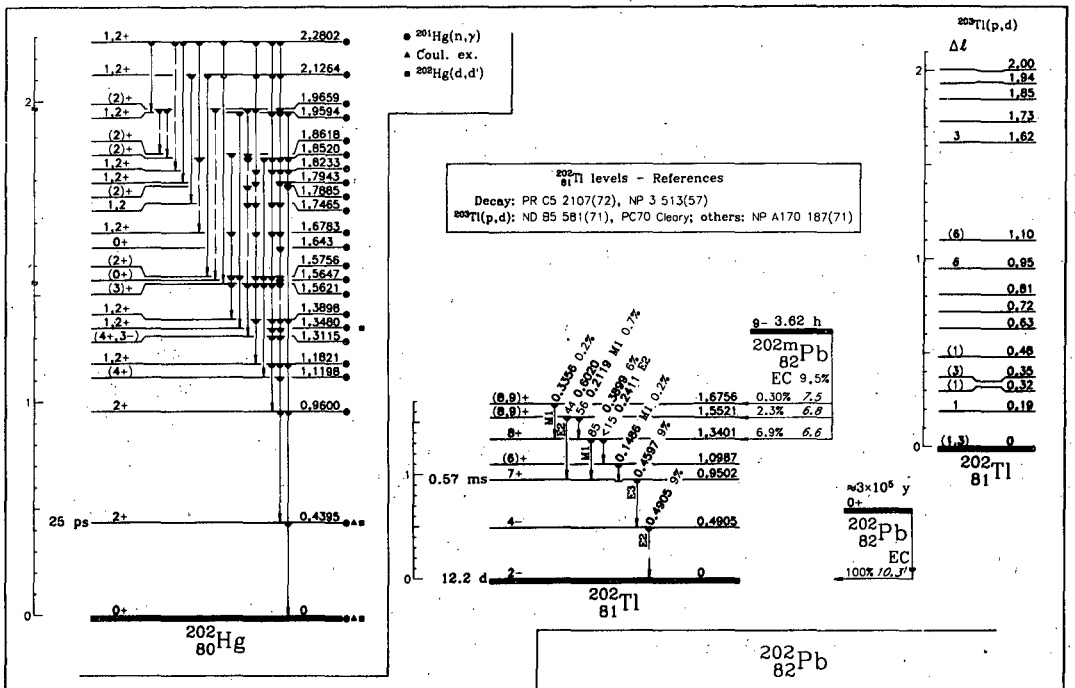


XBL 786-9445

Fig. 3a, b. A portion of the data for mass number A = 202 taken from the Table of Isotopes. Included is the mass-chain decay scheme which begins each A-chain compilation, tabulated data listings for several of the A = 202 isotopes, and "decay-level" schemes, "reaction" schemes, and their references for ^{202}Hg and ^{202}Tl. Note the stackplotting of all γ-ray transitions which proceed to the same final level in the ^{202}Hg reaction scheme.

(a) XBL 786-9445; (b) XBL 786-9446

(Image size has been reduced to conform to NDC format)



$^{202}_{81}$Tl

Δ: −25.988 *18* {ANDT 19 175(77)}
I: 2 *AB* {BAPS 3 319(58)}
π: EC {PCam 36 490(40), ZP 119 602(42)}; no β^+ {PR 79 1014(50)}
$t_{1/2}$: 12.23 *2* d {IIso 26 403(75)}; 12.4 *1* d {NP 75 81(66)}; 12.0 *1* d {Phca 23 1056(57)}; 12.50 *25* d {JINC 35 2139(73)}; **others:** {PR 86 565(52), PR 79 1014(50), PR 60 619(41)}
Class: A; **Ident:** chem, excit {PCam 36 490(40), PR 60 619(41)}
Prod: ^{202}Hg(d,2n) {PCam 36 490(40)}; ^{201}Hg(d,n) {Phca 25 326(59)}; ^{203}Tl(d,t) {Phca 25 326(59)}
γ: **0.43956** *1*, **0.52013** *7 Ge(Li)* {IIso 26 403(75)}
0.4394 *2*, **0.5203** *3*, **0.9597** *4 Ge(Li)* {IDO-17222(67)}
(**norm:** $\gamma_{0.440}$ (γ 91 *1*%), from level scheme, RED) $\gamma_{0.440}$ (t_γ100), $\gamma_{0.520}$ (t_γ1.0 *3*), $\gamma_{0.960}$ (t_γ0.13 *3*) *scint, scint–scint γγ coinc* {NP 75 81(66)}
0.4391 *4* ($K/L_{1+2}/L_3$ 3.3/1/0.29) *mag conv* {PR 92 918(53)}
Hg LX (t_γ1.86 *6*), Hg KX (t_γ100 *2*), $\gamma_{0.440}$ (t_γ100 *3*, e_K/γ ≈0.034, K/L 2.7) *mag conv, scint, ion ch* {Phca 23 1056(57), Phca 22 208(56)}
$\gamma_{0.440}$ (t_γ100, t_K 100), $\gamma_{0.960}$ (t_γ0.074 *5*, t_K 0.0133 *13*) *mag conv, scint* {NP 62 337(65)}
$\gamma_{0.440}$ (t_γ100), $\gamma_{0.520}$ (t_γ≈0.1), $\gamma_{0.960}$ (t_γ0.10 *3*) *scint, scint–scint γγ coinc* {ArkF 17 337(60)}
$\gamma_{0.440}$ (t_γ100), $\gamma_{0.520}$ (t_γ0.410 *6*), $\gamma_{0.960}$ (t_γ0.053 *8*) *scint, scint–scint γγ coinc* {Phca 25 326(59)}
others: {NP A184 157(72), NuoC s10v14 509(59)}
γγ(θ): {PL 26B 374(68)}
$t_{1/2}$(0.950): 570 *10* μs {CEA-R-2900(66)}, 565 *10* μs *delay coinc* {PR 112 1958(58)}, 585 *25* μs *delay coinc* {PR 112 1958(58)}, 600 *20* μs {NP A241 135(75)}, 608 *22* μs {NP A102 534(67), OesS 175p2 163(66)}, 536 *15* μs *delay coinc* {JINC 35 2139(73)}; **others:** {ZETF 45 1344(63), ArkF 12 237(57), PR 101 1067(56)}
EC(0): EC(L)/EC(K) 0.220 $^{+20}_{-15}$ {NP 75 81(66)}
EC(0.440): EC(L)/EC(K) 0.196 *2* {NP 75 81(66)}; **others:** {NuoC s10v14 509(59), Phca 25 333(59), Phca 23 1056(57), PPSL 69A 70(56), PR 96 548(54), PR 79 1014(50)}
EC(0.960): EC(L)/EC(K) 0.305 *20* {NP 75 81(66)}; **others:** {ArkF 17 337(60)}

$^{202}_{82}$Pb

Δ: −25.942 *11* {ANDT 19 175(77)}
π: EC {PR 96 548(54)}
$t_{1/2}$: ≈3×10^5 y *yield* {PR 96 548(54)}; **others:** {PR 78 191(50), PR 72 766(47)}
Class: A; **Ident:** chem, genet, mass spect {PR 96 548(54)}
Prod: ^{203}Tl(d,3n) {PR 96 548(54)}
$t_{1/2}$(levels): **1.383:** 1.97 *2* ns *delay coinc* {ZP A280 371(77)}, 2.00 *15* ns *delay coinc* {ArkF 14 439(59)}
2.208: 42 *4* ns *delay coinc* {NP A229 230(74)}

$^{202m}_{82}$Pb

Δ: −23.772 *11* {ANDT 19 175(77)}
π: IT 90.5%, EC 9.5% {PR C5 2107(72)}
$t_{1/2}$: 3.62 *3* h {ArkF 12 237(57)}; **others:** {Phca 20 521(54), PR 93 1433(54)}
Class: A; **Ident:** chem, excit {Phca 20 521(54), PR 93 1433(54)}; chem, mass spect {NP 3 513(57)}
Prod: ^{203}Tl(d,3n) {Phca 20 521(54), PR 93 1433(54)}; ^{203}Tl(p,2n) {PR C5 2107(72)}
γ with EC: (intensities relative to t_γ100 for $\gamma_{0.787}$ (with IT)) **0.14855** *15* (t_γ0.45 *15*, e_K/γ 2.9, K/L 6.1 *12*), **0.21192** *7* (t_γ1.5 *3*, e_{L1}/γ 0.14), **0.2411** *1* (t_K0.20 *2*, $K/L_{1+2}/L_3$ 18 *3*/10/4.0 *5*), **0.33555** *10* (t_γ0.45 *10*, e_K/γ 0.23, K/L ≈5), **0.38994** *7* (t_γ12.4 *10*, e_K/γ 0.18, K/L 6 *3*), **0.45972** *7* (t_γ17.3 *10*, e_L/γ 0.041, $K/L_{1+2}/L_3$ 18 *2*/10/2.0 *2*), **0.49047** *7* (t_γ18.4 *10*, e_L/γ 0.0073, $K/L_{1+2}/L_3$ 39 *11*/10/1.2 *3*), **0.60195** *8* (t_γ1.2 *1*, e_K/γ 0.016) *Ge(Li), mag conv, Ge(Li)–Ge(Li) γγ coinc* {PR C5 2107(72), NP 3 513(57), Phil s7v46 61(55), Phil s7v46 65(55), RED}
γ with IT: (**norm:** $\gamma_{0.422}$ (γ 86 *1*%), from level scheme, RED) **0.12475** *9* (t_γ1.1 *3*), **0.1293** *1* (t_γ0.08 *3*, e_L/γ ≈700, $K/L_1/L_2/L_3$ <0.02/≈0/1.9/1.0), **0.2403** *1* ($t_\gamma(\gamma_{0.240}+\gamma_{0.241}$(with EC)) 2.2 *3*, t_K0.31 *2*, K/L 5.0 *6*), **0.41732** *1* (t_γ0.82), **0.42212** *6* (t_γ172 *9*, e_K/γ assumed 0.030, $K/L_{1+2}/L_3$ 31 *4*/10/1.8 *3*), **0.5476** *3* (t_γ0.25 *8*, e_K/γ 0.35, $K/L_{1+2}/L_3$ 9 $^{+4}_{-2}$/10/1.7 *4*), **0.65749** *6* (t_γ65 *3*, e_K/γ 0.0053, K/L 5.5 *7*), **0.78699** *6* (t_γ100, e_K/γ 0.079, $K/L_{1+2}/L_3$ 13 *1*/10/≈1), **0.9545** *2* (t_γ2.0 *4*), **0.96070** *15* (t_γ18 *4 15*, e_K/γ 0.0056, $K/L_{1+2}/L_3$ 54 *8*/10/≈0.7) *Ge(Li), mag conv, Ge(Li)–Ge(Li) γγ coinc, mag–mag ee coinc* {PR C5 2107(72), NP 3 513(57), RED}
$\gamma_{0.422}$ (e_K/γ 0.032 *2*), $\gamma_{0.787}$ (e_K/γ 0.088 *4*) *semicond–scint eγ coinc* {NP 56 689(64)}
(intensity relative to t_γ100 for $\gamma_{0.787}$) **1.3828** *5* (t_γ6.4 *1*×10^{-4}, K/L 3.4 *7*) *Ge(Li), Si(Li) conv* {PR C12 338(75), RED}
γ: others: {ArkF 11 105(56), Phca 20 521(54), PR 93 1433(54)}

Fig. 3b

XBL 786-9446

of R. A. Meyer, are the first such tables to present γ-ray energies based on the new "gold standard,"[4] the 411.80441 15 keV transition in ^{198}Au decay.

Appendix IV has been added to include information on half-thicknesses for γ-ray absorption and on the range and stopping power for absorption of electrons and various nuclei (protons through ^{136}Xe) in different stopping media.

Appendix VII is an updated version of the Table of Nuclear Moments[5] published in 1975. This table will continue to be updated (production is computerized), and future editions will appear at 2- or 3-year intervals. It is expected that the seventh edition of the Table of Isotopes will be the last in the series started in 1940. The project is now part of the U.S. Nuclear Data Network (NDN) and is compiling mass chains for inclusion in the Evaluated Nuclear Structure Data File (ENDSF) and for publication in the Nuclear Data Sheets. The compilation and evaluation of mass chains A = 146-152 and A = 163-194 has been assigned to LBL as a principal responsibility.

The project has just completed the Nuclear Wallet Cards[6] on behalf of the NDN. This 84-page "shirt-pocket" booklet contains tables of nuclear properties, elemental properties, fundamental constants, and energy conversion factors. The data presented in the nuclear properties table are adopted values from the seventh edition of the Table of Isotopes, and include spin and parity assignment, mass excess, half-life (level widths are given for particle-unstable nuclides), natural abundances, and decay mode. The NDN plans to update the wallet cards on a 4-year cycle.

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6. V. S. Shirley and C. M. Lederer, editors; E. Browne, J. M. Dairiki, R. E. Doebler, A. A. Shihab-Eldin, L. J. Jardine, J. K. Tuli, A. B. Buyrn, J. M. H. Chong, and D. P. Kreitz, Nuclear Wallet Cards, produced by the Isotopes Project on Behalf of the U.S. Nuclear Data Network (1979). Copies are available from the National Nuclear Data Center, Brookhaven National Laboratory, Upton, New York, 11973.

B. RADIOISOTOPE DATING WITH THE 88-INCH CYCLOTRON*

R. A. Muller, E. J. Stephenson,† and T. S. Mast

Since July 1976, we have been studying and developing the potential of the 88-inch cyclotron for radioisotope detection and dating.[1-4] This cyclotron is much larger and more powerful than required for dating, but its flexibility and ability to tune rapidly to accelerate almost any isotope has enabled us to study several different applications. We now have demonstrated the sensitivity of using the cyclotron for the detection at natural concentrations of tritium, beryllium-10, carbon-14, and chlorine-36.

The key feature that allows direct detection of low-level radionuclides is the high energy of the emerging beam, which allows particle-identification techniques to be used on an atom-by-atom basis. Without such particle identification, direct counting is impossible because unstripped background ions with the same charge-to-mass ratio always appear in the beam. For carbon-14 the main background is nitrogen-14. In order to apply the particle identification techniques the nitrogen beam intensity must be reduced to the level which will not damage or cause pile-up in the silicon detectors. When tandem accelerators are used for radiocarbon dating[5] this reduction occurs in the negative ion source. For the cyclotron we have developed a technique that achieves the required reduction after acceleration. We have built and used for this purpose a simple gas cell which completely stops the nitrogen beam while allowing the carbon-14 atoms to pass.

The separation technique makes use of the fact that the range of carbon-14 atoms is approximately 30% longer than that of nitrogen-14. Uniformity of the stopping material is essential to ensure the minimum range-straggling for the nitrogen ions. The best material we have found to meet this requirement is gas, separated from the cyclotron vacuum by a thin window. We found that 1/3μ of gold foil will support

1 atm of pressure difference if supported by a grid with gaps no larger than 1/3 mm (Fig. 1). Gold and platinum are convenient window materials because their high atomic number Z inhibit nuclear charge-exchange interactions which can generate spurious carbon-14 atoms. For the same reason, xenon was chosen for the gas.

With the xenon gas cell we were able to eliminate completely 10 nA of ^{14}N ions. A plot of the nitrogen penetration as a function of xenon pressure is shown in Fig. 2, measured using a single particle detector. The curve shows discrimination to a level of 10^{-9}; in several hours of coincident detection using both ΔE and total E detection, not a single nitrogen event perturbed the xenon cell, implying a discrimination factor for the coincident system better than 10^{-14}.

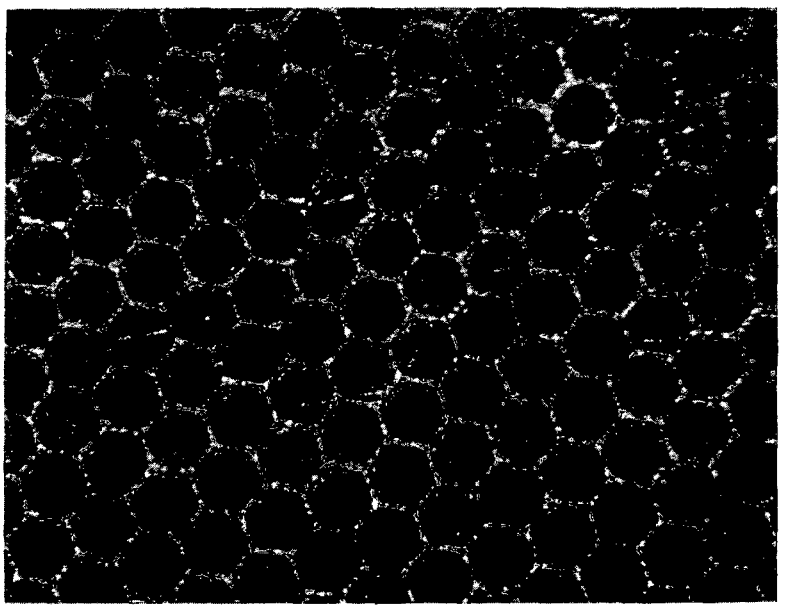

Fig. 1. The thin foil separating the xenon in the range cell from the vacuum of the cyclotron is supported on a tungsten grid, with hexagonal openings 0.33 mm in diameter. This grid is only 25 μ thick, and is supported in turn by a heavier 100 μ-thick tungsten grid with hexagonal openings 0.1 mm in diameter. The entire structure gives a clear aperture of 65%, over which 0.3 μ-thick gold foil can support a 1-atm pressure difference.

(XBL 781-163)

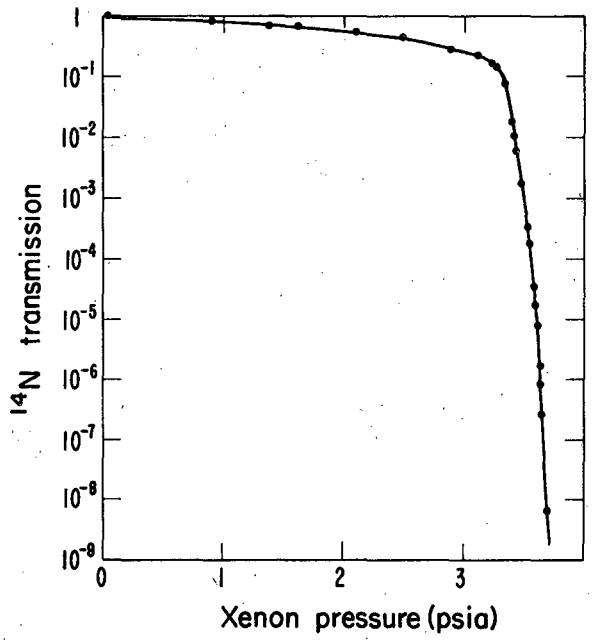

Fig. 2. Nitrogen-14 transmission through the xenon cell as a function of xenon pressure. The nitrogen-14 was detected with a single ionization chamber with a threshold energy loss of 0.8 MeV. When coincident detectors were used, the discrimination against nitrogen was found to be better than 10^{14}.

(XBL 783-2411)

For the range separation performed in the original tritium experiment[1] a single piece of aluminum foil was used. Because of the low level of background ^3He and its much shorter range than ^3H, non-uniformities in the foil were not critical. For beryllium-10 a solid foil is probably acceptable; for our measurements the xenon cell was used. For chlorine-36 the high uniformity of the xenon cell is essential. The "thickness" of the cell in milligrams per cm^2 can be adjusted remotely by changing the pressure of the xenon gas. The range-separation technique should prove to be valuable for those using tandems as well as cyclotrons.

Except for the case of carbon-14, the levels of background radioisotopes in real time from nuclear charge exchange reactions may, however, prove to be the ultimate limit to the cyclotron approach. For carbon-14 our sensitivity at present is limited by a high level of carbon-14 within the graphite-lined tank of the 88-inch cyclotron produced from years of scraping deuteron beams. The level of this carbon, which finds its way into the ion source during a run, has

varied from 1/3 to several times the level of carbon-14 in the sample being measured. We have made dates in spite of this background by rapidly switching sample gases to allow the comparison of the unknown with a blank and a reference standard. The results of a blind measurement[2,3] of a sample are shown in Fig. 3. In this run the measured age (in radiocarbon years) was 5900 ±800, with the large error dominated by the statistics of the background subtraction. The Rochester tandem group has a similar background; their ability to measure dates as old as forty thousand years is a reflection of the fact that their background is about a factor of ten lower than ours.

In the carbon-14 measurements the carbon was conveniently introduced to the ion source in the form of CO_2 gas. The efficiency for acceleration of the $^{14}C^{3+}$ ions could be varied between 10^{-5} and 3×10^{-4}; in a typical run it was 3×10^{-5}.

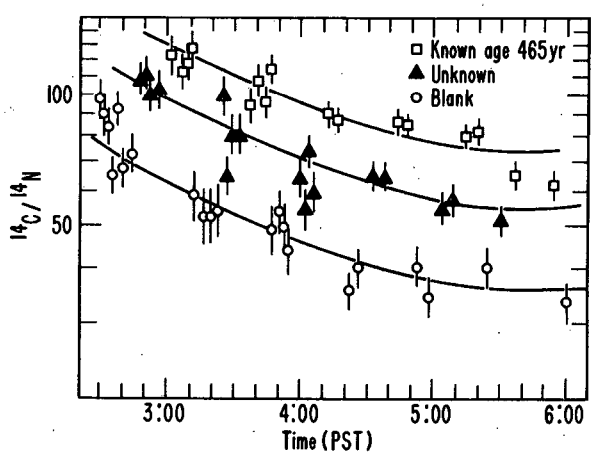

Fig. 3. The $^{14}C/^{14}N$ ratio as a function of time, for a blind sample.[2,3] The carbon-14 was measured with an ionization chamber, silicon-detector telescope. The nitrogen-14 was measured by integrating the current from slits which collimate the beam soon after it emerges from the cyclotron and well before it enters the xenon gas cell. Three samples were alternated: one of known age 465 years; a sample known to contain no carbon-14; and the unknown. The fit corresponds to an age of 5900 years, where the "standard" radiocarbon half-life of 5570 years has been assumed.

(XBL 7712-11088)

We have made nearly a dozen successful "nonblind" tests, and the successful "blind" test shown in the figure. More recently, however, we made a blind measurement in which our answer differed greatly from the answer achieved by decay-dating: we misestimated the age of an 8,000-year old sample dated by Rainer Berger to be 18,000 years old. This was the only collagen sample we have measured, and we suspect that impurities in the CO_2 affected the performance of the ion source, changing the level of background appropriate to subtract. The best hope for the elimination of such systematic errors lies in the elimination of the background. The easiest way to achieve this will be to use an external ion source which can pre-accelerate the ions to tens of keV before they enter the contaminated tank of the cyclotron. The design and construction of such a source is now under way, and we expect it to be operational later this year.

In our ^{10}Be measurements no comparable background has been detected. We have measured $^{10}Be/^{9}Be$ ratios in beryllium metal at the 10^{-9} level, comparable to that expected in sea floor sediments. We observed 800 ^{10}Be per second in our detectors, and the background was less than one count in five minutes. Our sensitivity for ^{10}Be is better than 10^{-14}, justifying all the optimism expressed in Ref. 1. A comparable sensitivity was achieved when BeO was substituted for beryllium metal in our Penning Ion Gauge (PIG) sputter source, but we have not yet achieved an accurate date with BeO.

Accurate ^{10}Be dating will require rapid cycling between samples of known and unknown concentrations. Since the samples are presently introduced in the back insert of the PIG source they cannot now be readily changed in the internal ion source. The new external ion source will allow this rapid cycling.

For ^{36}Cl our demonstrated sensitivity is 10^{-12} for the ratio $^{36}Cl/Cl$. This sensitivity is sufficiently good to make ^{36}Cl an attractive tool for measuring the age of water in potential nuclear waste storage sites, useful in determining the geologic isolation of the deep site from the surface.

After only one and a half years of development, the accelerator approach has already proven its potential for several radioisotopes. Except for the case of carbon-14, there have been no unantjcipated backgrounds, and we are optimistic that the full predicted[1] sensitivity of the accelerator approach will soon be utilized.

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C. ISOMERIC STATES IN ^{212}Bi*

P. A. Baisden, R. E. Leber, M. Nurmia, J. M. Nitschke, M. Michel, and A. Ghiorso

During a search for superheavy elements via the reaction of ^{48}Ca with ^{248}Cm we discovered several alpha lines around 10 MeV with a half-life of 25 ± 1 min.[1] In addition, a line at 11.66 MeV was observed and found to contain a longer-lived component of 9 ± 1 min in addition to the expected 45-sec half-life of ^{212m}Po.[2] Both activities could be produced by the bombardment of ^{208}Pb with ^{40}Ar, and also from ^{238}U with a variety of projectiles such as ^{40}Ar, ^{48}Ca and ^{136}Xe.

A spectrum of a source obtained by irradiating ^{238}U with ^{40}Ar followed by electrolytic dissolution and extraction of the Bi-Po-At fraction into diphenylthiocarbazone-CCl_4 at pH 2.5 is shown in Fig. 1; the doublet at 6.3 MeV was found to decay with the same 25-min half-life as the group at 10 MeV.

The 25-min activity was found to follow the chemistry of Bi through the technique of residue adsorption or chemisorption[3] and its mass

number was found to be 212 in three isotope separation runs made with chemically separated samples using the LBL Isotope Separator. Our studies indicate that this isomeric state, $^{212m1}Bi$, decays both by alpha emission to ^{208}Tl and by beta emission to excited levels in ^{212}Po, followed by the emission of "long-range" alpha particles to the ground state of ^{208}Pb.

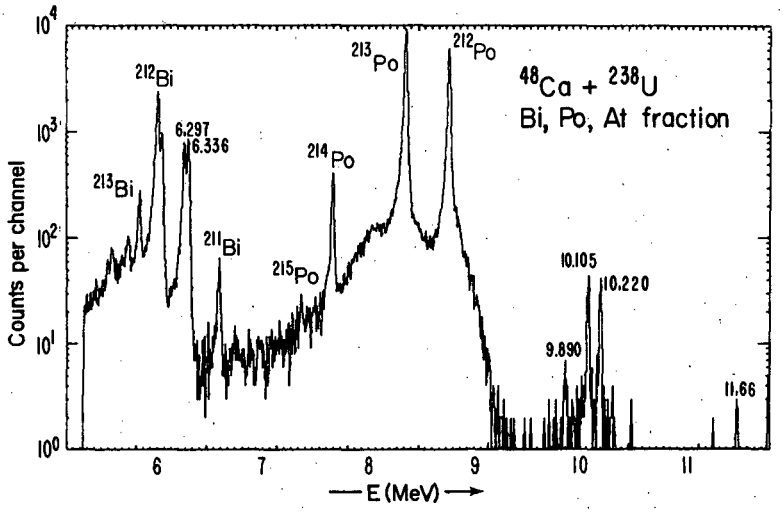

Fig. 1. Alpha spectrum of the Bi, Po and At fraction from ^{48}Ca + ^{238}U. Geometry 20%, resolution, FWHM = 25 keV. (XBL 783-332)

The fact that an isomeric state should exist in ^{212}Bi is suggested by analogy with the 9^- isomeric state in ^{210}Bi.[4-7] The configuration of ^{212}Bi, $(\pi h_{9/2})(\nu g_{9/2})^3$, differs from that of ^{210}Bi, $(\pi h_{9/2})(\nu g_{9/2})$, in that ^{212}Bi has two additional $g_{9/2}$ neutrons. Shell-model studies have been carried out on the ground state and low-lying states of the configuration $(\pi h_{9/2})(\nu g_{9/2})$ of ^{210}Bi by Kim and Rasmussen.[8] Their calculations, which are in excellent agreement with the experimental observations of Motz et al.,[9] indicate the level responsible for the isomeric state is a 9^- state located at 268 keV. Therefore, we suggest an analogous 9^- spin for the isomeric state in $^{212m1}Bi$.

Detailed shell-model calculations of the excited levels of ^{212}Po have been made by several authors. In one such calculation Glendenning and Harada, allowing for configuration mixing, predicted a state with $J\pi = 18^+$ to explain the 45-second ^{212m}Po.[10] Their results also indicate the possibility of another isomeric state J = 10-12 at an excitation energy of 1.2 MeV. On the other hand, calculations by Auerbach and Talmi, assuming no configuration mixing, indicate a spin of 16 for

^{212m}Po.[11] Likewise, their calculations also suggest a second isomeric state, however, of lower spin, around J = 8-10.

It is reasonable to assume that since the first excited state of ^{208}Pb is 2.6 MeV above the ground state, the 10-MeV group decays to the ground state of ^{208}Pb. This would place the levels in ^{212}Po responsible for the 10-MeV transitions at an excitation energy of 1.1 to 1.5 MeV. These levels are consistent with either of the shell-model calculations mentioned.

As a test for the assumption of a 9^- isomeric level in ^{212}Bi, one would expect a log ft value of 6-9 (first forbidden transition) for a beta decay from a 9^- to either an 8^+ or 10^+ state in ^{212}Po. In view of the possibility of gamma decay the ratio of alpha transitions from the 9^- state yields a lower limit of 7% for the beta branch to ^{212}Po. The resulting upper limit of 6.8 for the log ft value is then compatible with the spin assignment of 9^- for ^{212m1}Bi.

We were unable to obtain a definite elemental or mass assignment of the 9-min activity in the chemisorption and isotope separation experiments but we did find out that it is coprecipitated with CuS from an acidic solution. Since our ^{48}Ca + ^{248}Cm work showed that it is genetically related to the 45-sec ^{212m}Po, it could, in principle, be an isomer in ^{212}At, ^{212}Po or ^{212}Bi. The first possibility was eliminated when we observed that we could volatilize the ^{211}At-^{211}Po activity away from our sources while the 9-min and 25-min activities remained.

In their discovery work on ^{212m}Po, Perlman et al.[2] irradiated a lead oxide target with 116-MeV ^{11}B ions and separated a Po fraction by a combination of volatilization and cation exchange. They found that ratio of the ^{211}Po and ^{212m}Po activities was not changed by the chemical procedure if the latter was assumed to have a half-life of 45 seconds; this apparently rules out the possibility that the 9-min activity is another isomer in ^{212}Po feeding the 45-second state. It is also difficult to postulate a second isomer in ^{212}Po that would decay into the known ^{212m}Po and yet have the required long half-life against alpha decay.

The remaining possibility, that the 9-min activity is another isomeric state in ^{212}Bi which beta decays into ^{212m}Po, appears quite plausible. If one breaks the pair of $g_{9/2}$ neutrons in ^{212}Bi and recouples the four particles outside the ^{208}Pb core to maximum spin, a 15^-state is obtained.[12] We consider this state in ^{212}Bi the most likely explanation of the 9-min activity; a consequence of this assignment would be that the spin of ^{212m}Po would be 16 as suggested by Auerbach and Talmi.[11] A decay scheme of the two isomers is shown in Fig. 2.

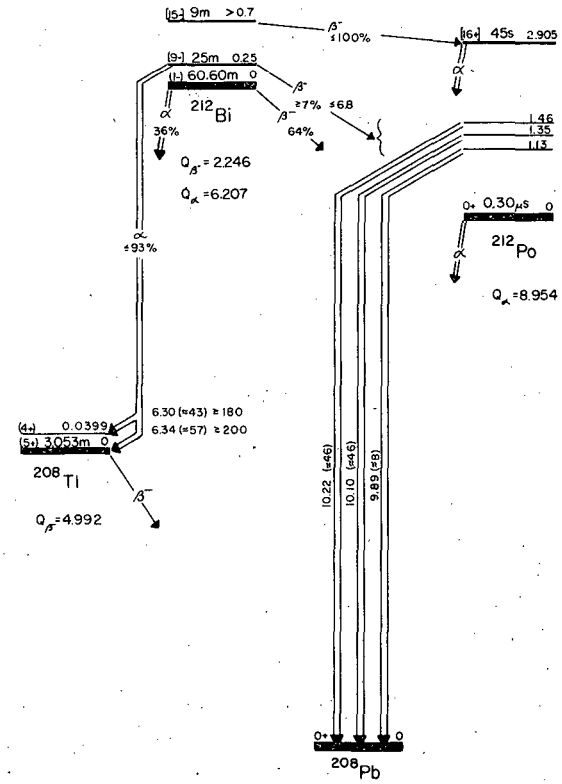

Fig. 2. Tentative decay scheme for isomeric states in ^{212}Bi. Relative alpha intensities are given in parentheses after the alpha energies. Other pertinent information shown, which was not explicitly determined in this work, was taken from Ref. 13. (XBL 783-330)

In conclusion we have shown evidence for the existence of two isomeric states in ^{212}Bi. Since these isomers are made in a variety of heavy reactions with heavy targets, the high energy alpha particles associated with their decay may be present in experiments aimed at the synthesis of superheavy elements. The possibility is accentuated by the fact that Bi is a homolog of element 115 and will follow the chemistry of the eka-Pb group of the superheavy elements.

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D. NEW EXPERIMENTAL INSIGHTS INTO THE PRODUCTION OF SUPERHEAVY ELEMENTS USING HEAVY ION REACTIONS*

R. J. Otto, D. J. Morrissey, G. T. Seaborg, and W. D. Loveland†

Attempts at the Lawrence Berkeley Laboratory to produce superheavy elements (SHE) using the reactions of ^{48}Ca with ^{248}Cm and ^{136}Xe with ^{238}U have been unsuccessful. These negative results have led us to consider the possibility that these reactions (and their associated mechanisms) do not lead to the formation of superheavy nuclei with sufficiently low excitation energies. Consequently, the number of surviving atoms of superheavy elements is well below our detection thresholds even with using relatively low estimates for prompt fission losses. A summary of some new experimental evidence, supporting the above hypothesis, is presented and possible alternative heavy-ion heavy-target combinations are suggested for SHE synthesis.

We have considered several possible reasons for negative results in the synthesis and identification of superheavy elements obtained at heavy-ion accelerator laboratories around the world. Due to the limited choice of targets above uranium, projectiles heavier than ^{40}Ar have been used. However, for projectile ions near and above the mass and charge of ^{40}Ar, quasi-elastic transfer and deep-inelastic transfer comprise a significant fraction of the total reaction cross section. The deep-inelastic transfer reaction has many characteristics that tend to obscure the observation of the complete fusion and compound nucleus-fission reactions. As a result, previous measurements of the fraction of the total reaction cross section corresponding to complete fusion can only be taken as upper limits. Furthermore, mass and energy distributions associated with binary events from heavy-ion reactions for example, $^{40}Ar + ^{238}U$ (Ref. 1) or $^{40}Ar + ^{243}Am$ (Ref. 2) in which complete fusion was assumed to occur, cannot be safely interpreted as corresponding to the fission of a compound nucleus.

A recently developed differential recoil range method[3] can be employed to further test this broad role of the deep-inelastic transfer process in the production of a wide range of products from bombardments with ^{40}Ar and similar ions. This method has been used to deduce the general shapes of angular distributions of products ranging from approximately one-half the mass of the compound composite system to products near the target.[4] These recoil range distributions from the reaction of 250 MeV ^{40}Ar with ^{238}U were correlated with a trend in the angular distribution of the projectile-like fragment as a function of ΔZ similar to the trend observed in the $^{40}Ar + ^{197}Au$ reaction.[5-9] This is a trend that has been interpreted as evidence for viewing the deep inelastic reaction mechanism as a dynamical diffusion process.[6,7,9] Complete fusion is ruled out for products with backward- or forward-

peaked angular distribution since the 1/sinθ -type angular distribution is expected for such a process.

These data indicated that non-complete fusion (and non-compound nuclear) processes accounted for an unexpectedly large portion of the mass distribution of the ^{48}Ca + ^{238}U reaction and, of the broad symmetric, previously labeled "fusion-fission," mass distribution of the ^{40}Ar + ^{238}U reaction.[1] Again, we can see that earlier work on the ^{40}Ar + ^{238}U system may have overestimated the cross section due to complete fusion processes. Thus we conclude that the use of ^{48}Ca as a projectile with heavy targets, considered a hopeful approach for the production of SHE's, must actually result in a much smaller production of compound nuclei than had been anticipated.

For ions heavier than argon, complete fusion-fission rapidly decreases, eliminating the possibility for production of SHE fission fragments in such reactions as krypton, xenon or uranium with uranium. In spite of the larger contribution from deep-inelastic transfer reactions, some complete fusion and compound nucleus formation is expected to occur in the ^{48}Ca + ^{248}Cm reaction. However, use of the proximity potential model[10] and the Bass model[11,12] predicts complete fusion thresholds 10 to 15 MeV higher than the interaction barrier, and the work of Saint-Simon et al.[13] using the similar reaction ^{40}Ar + ^{238}U provides experimental evidence for such an effect. As a result, the minimum attainable excitation energy for the compound nucleus ($^{296}116$) results in large prompt fission losses putting the SHE production level below the present experimental level of sensitivity.

For the ^{136}Xe + ^{238}U reaction, the probability of transferring the required number of protons and neutrons to reach the SHE region appears to be unacceptably low. This conclusion is supported by a study of the reaction of ^{136}Xe and ^{160}Gd.[14] The reaction $^{160}Gd(^{136}Xe;^{84}Kr,n's)^{212}Pb$ requires the transfer of 18 protons and 34 neutrons to ^{160}Gd from the ^{136}Xe projectile. This is the number of protons and neutrons required in a transfer from ^{136}Xe to ^{238}U to make ($^{290}110$) which is predicted to be in the "island of stability." Using a radiochemical separation procedure, an upper limit of 2×10^{-34} cm^2 was observed for production of ^{212}Pb in the reaction of 1150 MeV ^{136}Xe with a thick natural Gd target (21.9% ^{160}Gd).[14] The upper limit cross section for the reaction $^{160}Gd(^{136}Xe;^{84}Kr,n's)^{212}Pb$ is therefore 1×10^{-33} cm^2 or 1 nb. The 1 nb limit was applied to a similar or greater number of nucleons transferred from ^{136}Xe to ^{238}U by assuming that less than 10% of the Pb fragments fissioned and that the nucleon diffusion rates and the interaction times are nearly the same for the ^{136}Xe + ^{160}Gd and ^{136}Xe + ^{238}U reactions. It was pointed out that this limit is consistent with the theoretical prediction that the cross section for transfer of ~60 nucleons in

the Xe + U reaction is about 1 nb.[15] Figure 1 summarizes the results of this work. The cross section for SHE production is estimated to be $\leqslant 4 \times 10^{-36}$ cm^2.

$$^{136}_{54}Xe + ^{160}_{64}Gd \rightarrow ^{212}_{82}Pb + ^{84}_{36}Kr + n's$$

$$\sigma_{DIT} \leqslant 1 \times 10^{-33}\ cm^2$$

Transfer to target ($\Delta p = 18$, $\Delta n = 34$)

Loss by Fission?

$$^{136}_{54}Xe + ^{238}_{92}U \rightarrow ^{290}(110)_{180} + ^{84}_{36}Kr + n's$$

$$\sigma_{SHE} \leqslant 1 \times 10^{-33} \left[\frac{\Gamma_n}{\Gamma_n + \Gamma_f}\right]^x \leqslant 1 \times 10^{-33} \times 4 \times 10^{-3}$$

$$\sigma_{SHE} \leqslant 4 \times 10^{-36}\ cm^2$$

Fig. 1. An upper limit cross section for the production of SHE's in the $^{136}Xe + ^{238}U$ reaction based on the experiments using the $^{136}Xe + ^{160}Gd$ reaction. Values of x = 4 and $[\Gamma_n/(\Gamma_n+\Gamma_f)]^4 = 4 \times 10^{-3}$ were used.[14] (XBL 789-11116)

The possibility remains that transfer reactions using very heavy-ion projectiles such as ^{197}Au, ^{208}Pb, ^{238}U, or ^{244}Pu with ^{254}Es or ^{257}Fm targets could lead to the production of SHE nuclei at relatively low excitation energies.

Recent studies of the $^{238}U + ^{238}U$ reaction at Gesellschaft für Schwerionenforschung[16,17] show that, for a given average width in the charge dispersion (mass dispersion), the energy damped into internal excitation energy is less than in Xe transfer reactions.[18,15] Such an observation can be interpreted as supporting the idea that there should be significantly larger cross sections for the production of heavy transuranium elements in the reaction of U + U[16] than in the Xe + U reactions.[19] Evidence for such an effect can be seen by making

a comparison of the yields of Cf and Es isotopes (ΔZ = 6 and 7, respectively) from these two reactions, where the cross sections for the production of the more neutron-excessive isotopes are 10 to 10^2 times larger from the U + U reaction.[17] Such an effect suggests the use of a very heavy target such as ^{248}Cm, ^{249}Cf, ^{252}Cf, ^{254}Es, or ^{257}Fm with a heavy-ion beam of ^{238}U (or possibly ^{197}Au, ^{208}Pb, or ^{244}Pu) as a way to produce SHE's. Figure 2 shows a number of interesting transfer reactions. The ^{165}Ho and ^{248}Cm reaction shown first could be driven by the closed shell at Z = 50. However, the diffusion process would probably favor symmetric division into two fragments near ^{208}Pb.

$$^{165}_{67}Ho + ^{248}_{96}Cm \rightarrow ^{289}(113)_{176} + ^{124}_{50}Sn$$

$$^{165}_{67}Ho + ^{248}_{96}Cm \rightarrow ^{208}_{82}Pb + ^{205}_{81}Tl$$

$$^{238}_{92}U + ^{238}_{92}U \rightarrow ^{255}_{100}Fm + ^{221}_{84}Po \quad \sigma \approx 10^{-33}$$

Transfer ($\Delta p = 8$, $\Delta n = 9$)

$$^{254}_{99}Es + ^{238}_{92}U \rightarrow ^{271}(107)_{164} + ^{221}_{84}Po$$

Transfer ($\Delta p = 8$, $\Delta n = 9$)

$$^{257}_{100}Fm + ^{238}_{92}U \rightarrow ^{283}(110)_{173} + ^{212}_{82}Pb$$

Transfer ($\Delta p = 10$, $\Delta n = 16$)

Fig. 2. Hypothesized heavy-ion transfer reactions. Only the U+U reaction has been shown to occur experimentally.[17] No designation of emission of neutrons has been indicated. (XBL 789-11117)

Based on the results with the U + U reaction[17] studies at GSI to produce ^{255}Fm, an analogous reaction of ^{238}U with ^{254}Es is written to suggest the possibility of transfer reactions to produce elements near the SHE region with reasonable cross sections. However, the formation of SHE's requires a transfer with a larger neutron-to-proton ratio, as indicated in the reaction of ^{238}U with ^{257}Fm. It is important to note that the predicted stability of the products in the SHE region for these last two reactions varies from being unstable to having detectable half-lives.[20,21] Although such reactions would have many technical difficulties associated with them, these target- projectile combinations may provide a suitable reaction pathway to the formation of SHE's not available in the reactions that have been used up to now. The success of these experiments rely on the transfer reaction mechanisms and on an extrapolation of broad Gaussian distributions of primary products (before fission) around the target nucleus extending from the millibarn region into the nanobarn region. Also, the disadvantages of the extremely small amounts of ^{254}Es and ^{255}Fm available may more than offset these advantages for their use.

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